Tips for Inertial Electrostatic Confinement Fusion Investigators

(A Supplement to article "The World's Simplest Fusion Reactor, and How to Make It Work", published in the December 1998 _Analog_ magazine, a Dell publication.)

by Tom Ligon

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Acknowledgment: The uncredited photograph on the title page of the article referenced above was produced by Richard Hull, the Tesla coil guru of TCBOR. The photo shows a machine he built after reading a draft of the article and witnessing a demonstration of an early machine of mine.

INTRODUCTION

This is intended primarily for those who have read my article "The World's Simplest Fusion Reactor, and How to Make It Work" in the December 1998 _Analog_ magazine. In that article, I describe a simple machine, variously called a Farnsworth Fusor or Hirsch/Farnsworth machine, composed of concentric spherical electric grids in a vacuum chamber, which is capable of doing controlled hot nuclear fusion (well below breakeven). The device is characterized in the article as being so simple it could be done as a high school science project.

This is not some hocus-pocus pseudoscience, nor even a contrversial new discovery of some mysterious phenomenon. This is a working hot-fusion technlogy, which has been proven to work in one lab after another, for decades. It is based on straightforward classical physics. The key concept is Inertial Electrostatic Confinement (IEC) using either direct Ion Acceleration (IXL) or indirect ion acceleration using an Electron Acceleration (EXL) potential well. Ions are electrostatically accelerated in the same manner as in primitive linear particle accelerators, but spherically so that they converge to a high-density region.

Just because the machine is simple, and could potentially be built by a high-school student, this does not mean it is perfectly safe, nor should be attempted without a knowledgable advisor (or maybe MORE than one). On the contrary, aspects of it are lethally dangerous, and it is quite capable of doing nuclear reactions which should be done only with the advice and supervision of someone competent in "Health Physics" (nuclear safety), high voltage, and laboratory practices.

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WARNING

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The machine described in the article operates at around 10,000-15,000 volts, at currents sufficient to be lethal! Voltages this high can arc, corona, leak, and otherwise find their way into your body under circumstances where more common voltages may be perfectly safely contained. It cannot be stressed enough that strict high voltage safety practices must be followed at all times.

Other hazards exist in this project as well. It involves the use of vacuum equipment and pressurized, flammable gases, either of which can be dangerous. The construction is left largely to the individual researcher, but certainly one must use good safety practice in whatever shop skills are employed, and choose parts and materials safe and suitable for the job. The device described is barely capable of producing a detectable nuclear reaction, so this is actually one of the least of the hazards, but raising the voltage and power of the device, operating it for an extended time, or making other performance enhancements could potentially constitute a nuclear hazard.

READ AND UNDERSTAND ALL OF THE SAFETY TIPS BELOW, AND BECOME FAMILIAR WITH GENERAL LABORATORY SAFETY AND FIRST AID, AND BE SURE SOMEONE IS ON HAND WHO CAN RENDER AID IN CASE OF AN ACCIDENT.

Neither Tom Ligon nor _Analog_ accepts any responsibility for any death, accident, injury, screwup, financial loss, boo-boo, glowing in the dark, curled hair, browned shorts, or failure of the experimenter to hold proper health, property, and liability insurance. Stupidity, as Heinlein noted, is a CAPITAL OFFENSE!

GET AN ADVISOR, MAYBE MORE THAN ONE

Unless you are already skilled in all of the many fields required to build a working device, you are strongly warned to obtain assistance from someone who is. For a high-school student, or any relatively inexperienced worker, this probably means getting advice and supervision in virtually every hands-on aspect. I am particularly concerned about the immediate and deadly danger posed by the high voltage at which these devices operate, but there are also other hazards, some of which are potentially insidious, with their effects not becoming apparent for years.

While the nuclear danger of the device described in the article is expected to be minimal if built and operated as described, it is intended to produce “fast neutrons”, a form of radiation with a very high “relative biological effectiveness”, in other words -- especially deadly in high enough doses. Even if only a low and tolerable dose is expected, the dose should be verified. Also, since the proof of doing deuterium fusion is production of the characteristic fast neutrons that reaction produces, you will most certainly want to detect and quantify them. The methods and equipment for doing this are no trivial problems for the typical high-school student to solve.

Thus, one very important advantage of finding someone skilled in Health Physics (radiation safety) is that they may be able to loan you equipment and/or help you find scarce materials and

equipment, possibly saving you a small fortune. They can also help verify your claims of detecting neutrons.

If you are unable to find an advisor in a critical hardware phase, I recommend that you adjust the scope of your endeavour. While you may get more radiation exposure from days in front of a computer CRT than you would from a few minutes of operation of a machine intended to barely make detectable fusion, I think few people would consider computer simulations of IEC fusion devices to be too hazardous for a high school student. This is a field which has not been exhausted. Although typically tackled at the graduate level by Masters and PhD candidates, a sharp calculus whiz, particularly one with the talent to compete nationally at the high-school level, might reasonably make a meaningful contribution to the field. If you can get good advisors for fabrication, high voltage methods, vacuum, gas handling, etc., but not nuclear safety, you could build the machine but run it on ordinary hydrogen, still an interesting demonstration but without the nuclear aspect.

HIGH VOLTAGE POWER SUPPLY SAFETY.

The equipment described can cause INSTANT DEATH, painful shock or burns, and severe secondary injuries due to sudden involuntary muscle movement.

To lessen the chance of injury:

Touch high voltage components only after power to the apparatus has been doubly turned off (for example, switched off and unplugged, with the plug where you can see it), and with the high voltage circuit grounded with a safety connection.

Always work on or near the high voltage circuits with one hand only. It is generally best to keep the other hand in your pocket unless this would, for some bizarre reason, be hazardous in itself.

Always keep your body insulated from electrical ground when working near or touching any circuit which might conceivably be electrically "hot". Stand on a non-conductive surface such as clean, dry vinyl flooring, wearing non-conductive rubber-soled footwear. Do not allow any other portion of your body to come in contact with conductors. Be especially cautious of positions which would send electrical current through your torso (and thus your heart).

Have someone standing by in case of an accident. Be sure they know the danger, and know how to safely disconnect power to the apparatus, remove you from danger, apply CPR or other first aid, and summon help.

A non-conductive hook, cane, or similar device should be on-hand. This would be used to pull a victim off of a high-voltage circuit without endangering the rescuer.

It is recommended that the circuit be powered from a Ground Fault Circuit Interrupter. However, such a device will NOT prevent a shock hazard from the power supply described herein.

Use safe construction practices (especially insulation and grounding) so that no part of the system can inadvertently become electrically "hot".

Some materials ordinarily considered to be electrical insulators, such as wood and cloth, may conduct lethal current at high voltages.

The machine described in the article can produce voltages approaching 15,000 volts. The power source described is a 15 kV (15,000 V RMS), 60 mA 60 Hz alternating-current neon sign transformer. Transformers of this type are centertapped, that is the two high voltage terminals are each 7500 V RMS off of case ground, and the center tap is attached to the transformer's metal case. They are not constructed to be used in any other manner.

I once new a perfectly intelligent engineer who tried to ground one terminal of a neon sign transformer, use the other as the hot terminal at 15000 volts, and allow the transformer case to "float". So it floated to 7500V, and arced to the 120 V power leads coming in. BAD IDEA!

The 7500V value is RMS (root-mean-square) which means something similar to "average" (RMS voltage times RMS current gives actual average power in resistive loads). The voltage actually varies as a sine wave at 60 Hz AC, and the peak value is 1.414 x the RMS value. Thus, the peak value would be expected to be 10,600 V. Actually it is usually a little higher with this type of transformer, and may exceed 13,000V. The reason for this is that the transformer voltage is rated for use under load, and with no load the voltage will be somewhat higher.

The most natural way to convert the output of a transformer of this type to DC is to use a pair of high voltage diodes (rated at above the full current capacity of the transformer and over twice the peak voltage) to produce a Full Wave Center-Tapped Rectifier circuit. This type of circuit is described in most basic electronic texts. The diodes should each "point toward" the transformer high voltage terminals so that the supply produces negative output. HOWEVER, IT IS IMPORTANT TO REALIZE THAT, WHILE THE CIRCUIT SCHEMATIC IS VERY "ORDINARY", THE CONSTRUCTION METHODS ARE QUITE SPECIAL IN ORDER TO SAFELY HANDLE THE VOLTAGE!

High voltage diodes may be tricky to find. Some possible sources of supply are given at the end of this article, although a few may not care to deal with amateurs or in small quantities. There are specialty outfits that produce diodes directly capable of handling the required conditions, about 30 kilovolts (twice the peak supply voltage plus a margin) and at least 100 milliamps (the minimum rating recommended for the transformer specified). If you are unable to get such high-performance parts, you might consider using diodes for microwave oven power supplies, typically capable of 12kV at 300 mA. Three such diodes connected in series would suffice to replace one 30kV diode. You could even work with 1kV diodes, with 30 in series, encased in epoxy. This may or may not work due to any number of possible problems, but since such diodes in quantity are pennies apiece, if care is taken so a failure produces nothing worse than the stink of burned parts it is a possible alternative.

It is recommend that the neon sign transformer be powered by an adjustable autotransformer,

sometimes called by a trade name such as Variac. The neon sign transformer will draw around 7 amps, and so an autotransformer capable of delivering 10 amps is the best size to use. If one cannot be found used or borrowed, a source of supply for an economy model is listed at the end of this article. Use of an autotransformer allows you to bring the voltage up slowly, avoiding damage if the system is run at too high a pressure, or while conditioning the grids.

It is customary in such circuits to employ a "filter capacitor". This can be done at high voltage as well, but you must be aware that it greatly increases the hazards associated with the circuit. First, a capacitor can store a lethal charge for hours or days after the apparatus is turned off. Second, a capacitor makes it possible for the apparatus to produce brief pulses of current vastly above the capacity of the transformer. Finally, while not a safety issue, a large capacitor will usually make grid damage more of a problem for gridded IEC machines. It is possible to make a demonstration machine without a filter capacitor, and unless you are willing to accept the extra danger I recommend you work without a filter capacitor. More on this topic in a section below.

A strong, securely connected, and easily seen grounded safety lead should be installed on the equipment. This should have an insulated probe, plug, or clip which can be attached to the high voltage circuit to drain off any charge and assure the system is not dangerous. You should not work near or touch any high voltage circuit unless you can SEE this ground connection is good and can SEE the power is off and the supply unplugged.

Warning lamps to show power is on are an excellent idea, however remember that lamps can burn out, so don't trust a lamp to tell you a circuit is dead, just use it to warn you a circuit is live.

Do not try to build a high voltage circuit on an ordinary circuit board, particularly the cheap phenolic type with cellulose fibers. Don't use wood. Don't use cardboard. Don't use anything that you are not absolutely confident can handle the voltage! Among the better materials, you could consider Lexan (or comparable polycarbonate) sheet, garolite (high-performance phenolic intended for high voltage use), and porcelain. Plexiglas (or other acrylic) also works well but is a problem to cut and drill. My own preference is to use cylindrical porcelain standoffs on a polycarbonate board, with the components connected between the porcelain standoffs. The insulators must be kept clean -- any moisture, sweat, or other contamination can cause leakage of current. Porcelain insulators (frequently used in high-power transmitters, particularly those built to military specifications) can sometimes be found surplus and can be bought new from better electronic supply houses. Good plastic insulators can also be used and can be bought or fabricated.

Adequate component spacing must be allowed. The voltage employed can easily jump 1-2 centimeters, producing a vicious arc. It can also produce coronas (sizzling halos of ionized air) particularly if the air is humid.

Either arcs or coronas will produce ozone, a highly reactive form of oxygen that can rot rubber and peel the paint off of walls, so just imagine what it does to your lungs and eyes! Ozone has a sharp, "fresh" smell. If it starts to build up you should ventilate the work area. It can also be destroyed by circulating it over an activated charcoal filter. It is also often produced by laser printers and photocopiers, and the same measures should be used to control ozone from them.

The power supply should be enclosed to prevent accidental contact. It is very easy, when handling a piece of wire or a long metal object, to accidentally come in contact with a high voltage circuit. The enclosure can be wood (if spaced well away from the electrical components and wiring), plastic, or metal (if electrically grounded and spaced well away from the components and wiring).

Inside the power supply enclosure, ordinary wiring may be used, even uninsulated wiring, if the spacing is adequate. Some insulations will, in fact, catch fire if exposed to a high voltage arc, and thin electrical insulation will do little to protect against such arcs anyway. BUT ...

OUTSIDE THE ENCLOSURE OF THE POWER SUPPLY you must use specially insulated high voltage wire. Such wire is sold for making neon signs, or you could consider using non-resistance spark plug wire. Some electronic supply houses may also have wire with very high voltage insulation. It is best to supplement the insulation with an extra layer, with "Teflon" or similar flourocarbon tubing being a good choice. The outer tubing helps protect the inner insulation from cuts, scrapes, etc, and may prevent arcing from unseen pinholes or cuts in the primary wire insulation. It is also a good idea to support and route the wire through clean PVC electrical conduit to as great a degree as practical. Avoid polyethylene tubing or other materials which could catch fire in an arc.

The electrical feedthru carrying high voltage into the test chamber typically has an exposed terminal. This terminal should be covered to prevent accidental contact. A plastic cup can be slotted and fixed over the insulator to do this (allow at least 2 cm of space between the terminal and cup), or the terminal can be insulated with a heavy application of electricians splicing tape (a gummy, stretchy, rubbery tape that seals to itself and forms an excellent high voltage insulation, which MUST NOT BE CONFUSED WITH ORDINARY VINYL ELECTRICAL TAPE).

Measuring current to the test requires a little thought. You could attach a milliamp meter in the high voltage output lead, but it would have to be enclosed in an insulated box, and covered with a thick, clear plastic cover. More commonly, the meter is attached in the ground circuit connecting the test chamber to the high voltage supply. IT IS ABSOLUTELY IMPERATIVE THAT ANY METERING CIRCUIT IN THE GROUND LINE BE SECURELY WIRED IN SO THAT IT CANNOT BE DISCONNECTED! FAILURE TO DO SO CAN MAKE THE DISCONNECTED PART OF THE SYSTEM GO TO HIGH VOLTAGE! In otherwords, don't hook up an ordinary multimeter, equipped with banana plug or pin leads, in this role, nor use clip leads, unless you have a DEATH WISH!

Some part of the system MUST be electrically grounded (hooked to the building electrical ground). For example, if using conventional US NEMA 5-15 120V household power outlets you could ground the system by the U-prong of the power cord, and you might also connect to a secondary ground such as a metal electrical conduit. The only way to avoid this would be to put the whole apparatus in a big insulated box and never touch it. I would recommend grounding the test chamber case (assuming it is metal or has a metal base), and electrically isolating the transformer case, which should be enclosed with the high voltage components. The transformer case is then grounded through the current metering circuit. You cannot directly ground both

transformer and test chamber if you use a meter between them.

It is also a really good idea to have a second ground path between the test chamber and the high voltage supply in which a pair of low-voltage zener diodes in series but opposite polarity are used. If the meter should become disconnected or faulty, this path would limit the voltage to about the zener breakdown voltage. This can also be done with several regular silicon diodes in series, with two such sets in parallel (these will start to conduct at about 0.6V per diode). Choose the components so that the meter you are using operates at a much lower voltage drop, otherwise the meter will read too low.

Measuring high voltage is also tricky. You can buy a special probe which attaches to a digital multimeter, which divides the voltage by a factor of 1000. This allows you to read the meter so that volts become kilovolts. However, you can also build-in a voltage divider to the circuit. Don't expect to find the resistors to do this at Radio Shack -- in fact they can be quite hard to find at all. A source of surplus parts is listed at the end of the article which usually stocks them. The resistor to measure this circuit will typically be about a gigaohm (that's a billion ohms) and should be several inches long to handle the voltage safely (resistors of that physical size and resistance will handle the power, too). Be aware that if you hook such a resistor up to an ordinary ohm-meter the meter will think the resistor is an open circuit. Also be aware that a greasy handprint or any moisture down the side of the resistor will throw its resistance way off. Also be aware that the amount of current flowing through such a resistor is insufficient to move even the most sensitive mechanical meter movement -- you need to use a high-impedance electronic meter, which typically means a digital meter. The meter must be shunted with a second resistor, which can be a plain-old low-voltage type, with the value selected to give the desired reading on the meter. Any basic electronics book will describe how to build a voltage divider. You will need to borrow a calibrated high voltage meter to tweak the circuit for full accuracy (gigaohm resistors are not generally very precise, especially the surplus variety).

An additional benefit to using a built-in voltage divider is that it will help bleed off the charge when you turn the system off. This is especially vital if you decide to use a filter capacitor. Be aware that the rate of discharge will probably be very slow, and the bleed should not be used in place of a grounded safety strap.

Be sure the components used can easily handle the full power of the power supply shorted through them.

The transformer specified is designed to be internally current-limited, but the current limit is not a hard-and-fast number, nor is it based on a simple resistance. It can put out somewhat above 60 mA, and if filter capacitors are used it can momentarily put out amps, tens of amps ... kiloamps, hey, how big a capacitor did you put on that sucker, anyway? As a general rule, anything over 50mA is considered capable of killing a healthy adult (and a lot less than that can hurt like a sumbitch). LIKE I KEEP SAYING, THIS THING CAN KILL!

CAPACITOR AND INDUCTOR FILTERS

An unfiltered 60 mA high voltage power supply MIGHT not kill you if you are wearing rubber-soled shoes, etc., and don't do more than get a little zap. Might leave a hole in your skin with smoke coming out of it, and a great deal of pain, or maybe numbness for a day or two, but it is possible you would live through it. But if you have even a small filter capacitor on the supply, your first shock will probably be your last. Capacitors store charge, and CHARGE KILLS. Charge remains long after the system has been turned off, and can even come from static sources with the machine off! Use a grounded probe with an insulated handle to short out the capacitor before working on or near the high voltage system, and KEEP THE HIGH VOLTAGE LEAD GROUNDED when not in operation.

If you do choose to use a filter capacitor on your power supply, you will greatly magnify a pesky effect that Hirsch-type IEC machines experience: bright flashes from the central grid. These probably should be classified as "pulsed anomolous glow discharge" (you _Infinite Energy_ subscribers will suddenly perk your ears up). These occur most frequently with newly installed grids, and must be gradually "burned out" by slowly raising the voltage. They probably result from contamination on the grid by "low work-function" materials (things which give up electrons easily). The alkali elements do this, as do diamond films and certain other forms of carbon. Fingerprints should be suspected.

If the filter capacitor is large enough to significantly reduce ripple at currents in the 20 mA and above range where detectable fusion is likely, you can expect the flashes to be highly destructive. You may find sections of grid missing from time to time. Your options are to under-filter the power supply, or add inductive filtering, which suppresses sudden current pulses. Both capacitive and inductive filtering techniques are covered in the Amateur Radio Handbook published by the American Radio Relay League, and in other electronics texts.

The problem is, the required inductor size will be quite large, and it may be impractical to buy one which is capable of withstanding the high voltage of these supplies. There is a poor-boy alternative. You can buy a toroidal inductor or inductor core (the powerded iron type is best, and replace the windings with teflon-insulated wire to improve the high voltage performance. This will probably result in an inductor too small to reach the "critical value" calculated for good filtering. However, one additional trick will make it pretty effective at killing the destructive flashes -- add a single turn of heavy wire shorted to itself. This turns the inductor into a transformer, one with a short-circuited secondary. Any sudden pulse through the coil will induce a large current in the shorted loop, and really take the wind out of the pulse. This wastes some energy, but the energy it wastes is energy that would go into vaporizing the grid.

RADIATION HAZARDS

The apparatus described can produce three types of harmful radiation: x-rays, ultraviolet, and neutrons.

X-rays are produced when high energy electrons strike high-atomic-number targets. Electrons coming from the inner grid and hitting stainless steel walls or outer grid wires would be possible

sources. Colliding high-energy ions can also release essentially identical radiation (physicists may nit-pick over the name, but the hazard and precautions are essentially unchanged). If you stay below 15 kV the x-ray problem should not be serious, and a thin metal barrier (like metal chamber walls) should all but stop them. Your computer monitor cranks out worse x-rays, and is also shielded with thin metal. If, on the other hand, you decide to join the ranks of the serious researchers and crank up the voltage, you must absolutely take appropriate precautions, which are beyond the scope of this article.

Electrical discharges in hydrogen gas are commonly used to produce ultraviolet radiation at short wavelengths. This is pretty hot radiation, the sort that can cause a rapid "sunburn", eye damage, and skin cancer. Fortunately, it doesn't penetrate glass very well. I've been told it also does not penetrate clear plastics, but an itchy sensation on my cheeks tells me otherwise.

While it is possible to make a low-grade Fusor in a plastic vacuum dessicator chamber, I do not recommend it and three of the reasons are that it will not stop x-rays, may not stop UV, and also can't take heat, which the Fusor will produce. Plastic chambers are also prone to outgassing and are difficult to get down to the required pressure. Trust me, I tried a plastic vacuum chamber, and it is a waste of money as well as a possible danger.

Glass chambers can be used if they are a type intended for high vacuum use, and if used with a safety shield. However, they don't stop x-rays very well, and can implode if they have been damaged or are hit by anything. Use a metal chamber if at all possible, with a good-quality glass window built for vacuum use.

Neutrons are neutral subatomic particles, which will go right through the walls of the test chamber, hardly affected. In most cases, fears that "radiation" (x-rays, gamma rays, alpha particles, and beta particles) will make things radioactive are just plain ignorance. But neutrons CAN make things radioactive. When they hit another nucleus and are captured by it, they cause elemental transmutations, frequently into unstable isotopes. Beyond that, neutrons coming off of deuterium fusion reactions have hellacious energy, several million electron volts worth. They hit HARD, knocking atoms clean out of molecules and causing other unhealthy effects on living things. One would be well advised to avoid being hit by too many of these nasty little buggers, which are just about the worst type of radiation you can encounter.

Fortunately, the machine described, operating at under 15kV, does not make many neutrons. Operating at the most optimistic output, based on one really good 15-second burst I saw using a larger power supply, the machine should not be able to produce more than about 300,000 neutrons a second, which would require 12 days at 1 meter away before you picked up a dose high enough to even START to worry. This on a machine on which the grid life is probably under 20 minutes if the grid is made of stainless steel. More likely neutron production will be down in the hard-to-detect range of under 10,000 per second. These will radiate off spherically, so only a fraction will hit someone standing to one side.

The best shielding for most radiations, neuts and x-rays included, is the inverse square law. Put some distance between you and the source. An excellent neutron shield is water "poisoned" with boron. Fill a large trashcan with water and dissolve a box of borax (yup, the 20 mule-team

laundry product will do just fine) in it, then put the trashcan between you and the Fusor. Boron is a really aggressive neutron absorber frequently used to kill fission reactions. You can also add a little boric acid to it (also a neutron poison) and use it to make your Halloween or Christmas pagent costume fire retardant, and I'll wager if you have a cockroach problem it will soon go away. It is a little toxic (read the box), so keep pets and small children away.

Watching the glow of the reaction through a mirror would allow you to stay behind such a neutron shield. X-rays will not reflect from a glass mirror. With such precautions the already small radiation hazard from the machine described would be virtually zero.

Deuterium gas is not radioactive. It is a stable isotope of hydrogen found in nature in trace quantities, and can generally be purchased without special license from compressed gas suppliers, including some welding supply houses. Tritium gas, on the other hand, is quite radioactive, and can only be purchased and used with a special license and safety precautions. The use of tritium gas for these experiments is definitely NOT recommended except when conducted by properly licensed facilities run by knowedgable experimenters and overseen by professional Health Physicists.

FABRICATION SAFETY

As stated earlier, the great variety of fabrication techniques that could potentially be employed go far beyond any ability to address in this article. Please do not attempt to do any potentially hazardous operations without adequate instruction, supervision, and safety equipment.

In most, if not all, cases, this means wearing APPROPRIATE EYE PROTECTION.

In some cases, this may also require wearing HEARING PROTECTION.

Operations producing dust or noxious gases may require BREATHING PROTECTION.

Operations involving toxic compounds require APPROPRIATE EXPOSURE PROTECTION and SAFE DISPOSAL.

One operation does warrant special mention, as it is somewhat unusual and is likely to be needed in virtually all implementations of this apparatus. The absolute best way to physically support and get high voltage to the central grid of a Hirsch-type fusor is by running a wire through a CERAMIC TUBE, and the best choice for the tube is ALUMINA, an oxide of aluminum. Alumina tubing is readily available and not too expensive in the sizes and amounts needed for this work. However, it is the darndest stuff to work with you ever saw -- its strength and hardness are simply amazing. It defies ordinary tools, and usually cannot be cut by simple scoring as glass tubing can. The best way I have found to cut alumina tubing is using a high-speed mini-grinder (Moto-Tool or similar) and a diamond abrasive cutoff wheel. Don't even bother with the usual abrasive wheels for this type of tool as they simply disintegrate when they hit alumina. Small diamond wheels for these tools are not too expensive, typically under $20 for a set of 5 blades. Special safety precautions apply to cutting alumina:

EYE PROTECTION ABSOLUTELY REQUIRED! Your eye is no match for bits of diamond and alumna grit flying about.

BREATHING PROTECTION MANDATORY! Alumna dust from such grinding is very fine and should be expected to cause long-term lung problems if inhaled, similar to silicosis. For small quantities of dust (cutting a few small pieces of tubing) it may be best to work outside in a stiff breeze or with a strong exhaust fan pulling the dust outside to an unoccupied area, then clean up the area with a damp sponge. A good, properly-fit dust mask intended for very fine dust should be worn as a back-up. For larger quantities of dust, refer to current OSHA regulations for appropriate protection.

HEARING PROTECTION RECOMMENDED. High-speed grinding without hearing protection may reduce your ability to appreciate good music or hear dinner bells.

GAS CHOICES AND COMPRESSED GAS SAFETY

It is not absolutely necessary to run a Fusor-type machine on deuterium. You can do interesting, educational, and worthwhile non-nuclear tests using trace background gas in the system (typically mostly air or water vapor). Hydrogen gas is also readily available and cheap, and behaves very much like deuterium except that the ions move faster (they are half the mass of deuterium ions) and will not fuse at the voltages the machine will operate at. Heavy inert gases such as argon or xenon would make pretty glows in a Fusor, but be warned that they multiply ionize, and so multiply the acceleration of the grid: you might be using 10kV and getting 40 keV ions if the charge on each ion is +4, for example. This might get you into a radiation hazard area.

UNDER NO CIRCUMSTANCES SHOULD YOU USE BOTTLED OXYGEN OR OTHER OXIDIZING GASES, AS THESE PRESENT SPECIAL AND VERY SERIOUS SAFETY CONCERNS!

Both hydrogen and deuterium are extremely flammable (remember the Hindenberg)! Use them in a well-ventilated area, as free from ignition sources as possible, and limit the amount by using the smallest practical container. Use appropriate hardware and use it appropriately (I shudder to remember the day I found a large 20-liter hydrogen bottle empty due to a cut piece of teflon tubing that had been used instead of the recommended stainless steel).

The pressure in a commercial gas cylinder is typically up in the thousands of pounds per square inch. This presents all sorts of hazards. Information on safe handling is available from gas suppliers and in most lab safety books. Get the information, read it, and take it seriously.

Deuterium is slightly toxic when incorporated into biological materials, such as water. This is due to the additional mass: deuterium atoms react slightly slower than hydrogen atoms, which is enough to throw off some biochemical systems.

You should not need much deuterium or hydrogen if you keep the system tight and are not sloppy with your useage. A "lecture bottle" contains more than enough if used wisely. Recent prices for lecture bottles of deuterium run from $140 to $250. In addition, you will need a pressure regulator intended for hydrogen, preferably a two-stage regulator, designed for the lowest pressure you can get, probably 15 psig maximum. These ain't exactly cheap.

WARNING -- The use of a sample bottle recommended below is safe ONLY IF THE BOTTLE IS FILLED TO EXTREMELY LOW PRESSURE and ONLY IF THE BOTTLE IS FIRST EVACUATED OF AIR. The intent is to avoid the need for a regulator and to eliminate the hazards of high-pressure gas, but this advantage would be lost if the cylinder is filled beyond the lowest pressure needed, typically 10 psig or less, or filled with an explosive mixture of air and hydrogen.

An interesting way around the need for pressure bottles and expensive regulators may be available if you are in a position to share a bottle of gas or can pursuade someone to give you a small sample. In this case, all you need is a "sample bottle" of perhaps a half a liter or liter capacity. You could potentially use a clean 14- or 16-ounce propane bottle for this, if you carefully fill it to no more than 10 psig. To fill any sample bottle, you must first pump out all the air or gas using a vacuum pump. Then fill it partway and pump it out again, repeating this several times. Finally, fill it up to the desired pressure. Mechanical pressure/vacuum gages for this task are readily available from industrial suppliers for around $10. There will be some residual “odorant” gas, typically a sulfurous mercaptan, left in a propane bottle.

Hydrogen and deuterium gas should be run through hard lines wherever possible, preferably stainless steel. The best connections are Swage-Lok or similar systems employing two-piece ferrules. Use these according to the manufacturer's directions. Copper lines may break at the connections if flexed. If flexible lines are required, welding-gas-hoses may be the safest bet.

Leak test all pressurized joints using soapy water or a leak-check solution such as "Snoop". Not only will this help avoid fire or explosion, it may save the considerable heartache of finding the contents of an expensive bottle of deuterium have mysteriously vanished.

GRID CONSTRUCTION

Figure 2 in the _Analog_ article shows the general construction of a grid. Stainless steel welding wire of about 0.025" diameter works fairly well and is cheap and readily available. However, if you can obtain wire made from one of several "refractory metals" it make a better inner grid, as inner stainless steel grids are not especially durable, and may have a life of only minutes at power levels sufficient to produce measurable fusion (expect the inner grid to run red hot from ion bombardment if significant fusion is occurring). Tantalum, rhenium, and tungsten are considered refractory metals. Stainless steel works fine for the outer grid.

Tantalum has the lowest melting point of the three, but is a big improvement over stainless steel. It spot-welds readily if it is cleaned of all oxide and contamination prior to welding.

Rhenium is an excellent choice, but expensive. Fortunately you do not require much. It also spot-welds fairly easily.

Tungsten has the highest melting point of any metal, and it is reasonably readily available. Tungsten can be run white-hot without melting (although even tungsten grids can be damaged by extreme ion bombardment). Unfortunately, tungsten tends to make brittle spot-welds. If you are among the privledged few who know how to make durable welds with this tempermental metal, by all means consider using it. Otherwise, expect problems.

After the center grid is made, spot-weld a wire to one grid-wire intersection and bend it out perpendicular to the grid. This will be the lead to bring power to the grid. Run this wire through an alumina tube to the chamber's high voltage feedthru, where it can usually be attached by a mechanical friction joint (I sometimes wind the end of the wire into a coil and slip it over the lead of the feedthru). You may have to replace or adjust the grid so be sure your attachment method allows this. Overlapping sections of different-diameter tubing may be used to cover the joint. The outer grid is either grounded to the chamber walls or may be connected to its own feed-thru if you wish to try adjusting its voltage, which may be useful for controlling ionization.

The spot-welder I use for these grids is an older model with a capacity of 80 joules (80 watt-seconds). I usually adjust it down to 20-30 joules. A spot-welder uses a bank of electrolytic capacitors charged up to a fairly high voltage, typically up to 400 volts. When the desired energy level is reached (calculated from the capacitance and voltage by a simple formula found in basic electronics texts) the capacitor bank is discharged through a step-down transformer so that a pulse of low voltage but very high current is produced in the secondary winding. This pulse is delivered to a pair of copper rods with the "work" pinched between them. A good weld requires modest pressure be applied to the parts being joined, and a short jolt of high current flows through the point of contact between them.

Practice with scrap wire before building a grid, particularly if you are using expensive, hard-to-find metal.

There are probably several useful tricks one can do with grid design which will improve IEC performance. Be aware, however, that you are not the only person doing such experiments. While the original patents held by P. T. Farnsworth and Robert Hirsch, on which the _Analog_ article were based, have long since expired, there are active patents in the field. The Fusion Studies Laboratory under Dr. George Miley at the University of Illinois at Urbana-Champaign holds active patents, and since they have commercial aspirations in the IEC area you can expect them to get a bit testy if you steal their ideas. There is also some activity at Los Alamos and elsewhere. If you plan to try improved designs, particularly if you intend to publish or sell them, you would be well advised to do a patent search and retain a lawyer skilled in the field. The list of patents at the end of this article is incomplete, intended only as a starting place.

SOME THEORETICAL TIPS

This section presumes a good general science knowledge, including basic physics, chemistry, and electricity, plus basic algegra and geometry and the ability to solve "word problems".

I will not attempt to give a complete tutorial on the subject of nuclear fusion or the theoretical basis for the Farnsworth Fusor or Inertial Electrostatic Confinement (IEC). Dive into the many textbooks on nuclear physics and look up the referenced IEC papers for a complete understanding. What follows is only a brief introduction to give the reader an idea of the scope of the problem.

For each nuclear reaction involving collisions, which is the type involved in fusion, there is a parameter called "crossection". There are many types of crossection which may be encountered, but the one you are most interested in is "fusion crossection." This is not a fixed number, but typically increases with the kinetic energy (and velocity and "temperature") of the particle or particles involved (there is a maximum energy above which crossection will fall).

Crossections are all given in units of area. Essentially, they are "target size". Imagine you have a shooting gallery full of targets, and you are randomly firing small BBs into the gallery. You would calculate the likelihood of hitting a target from the area of the target (the crossection), their density (how much target area is there per area of shooting gallery), and how many BBs you fire at them.

In the case of fusion, picture that the target is a ball of modeling clay. If it is hit by a slow BB, the BB will just bounce off, so the crossection for the BB sticking is zero. If the BB is traveling a little faster, it may stick, but only if it hits dead center, so the target acts as if it is smaller than its actual physical size. If traveling even faster, the BB will stick if it hits anyplace on the target. If traveling a lot faster than that, the BB may just go clean through the target, possibly splattering the target in the process. Thus, fusion crossections are typically negligible at low energy, rise progressively as energy increases, to a maximum above which crossection falls with energy.

Hydrogen has a very poor fusion crossection. The nuclei are protons, with a mass of 1 AMU and a charge of +1, so Coulomb repulsion (mutual repulsion of like charges) is high compared to the mass. True hydrogen fusion occurs only in stars, and even then usually by a circuitous catalytic route, and the H-H reaction is not considered a practical fusion system for the near future. Deuterium nuclei are a proton and a neutron, with a mass of 2 a charge still +1, so they have more momentum compared to their charge with which they can better overcome the Coulomb barrier. Furthermore, the charge is on one end of the nucleus, and if the nuclei approach neutron to neutron they have a slight advantage. Deuterium thus has a much better fusion crossection than hydrogen. Tritium is two neutrons and a proton, mass 3 and charge still +1. Deuterium-Tritium fusion is about the easiest of the fusion reactions to do, i.e. it has the highest crossection and can go at fairly low kinetic energy.

The most commonly used unit of crossection is the "barn." One barn is 1e-24 (one times ten to the minus 24) square centimeters, or 1e-28 <<<CHECK CHECK CHECK square meters. Pretty small, you say? Actually, legend has it that a physicist was one day measuring collision crossections of various materials and found a really big one. This esteemed researcher said

something like, "Wow, that crossection is as big as a barn!" People who work with subatomic particles frequently have a unique perspective, not to mention a peculiar sense of humor when it comes to naming things. Typical D-D fusion crossections at the 10keV range in an IEC machine are around 0.0002 barns (in the centeral region) to 0.001 barns (for head-on collisions).

Fusion reaction crossections are published in a number of nuclear physics texts, but should be used with some caution. Be aware of the type of collision being described by the crossection. The interaction between two nuclei hitting head-on at the same energy, two nuclei hitting at an angle at the same energy, two nuclei hitting at random energies and angles within the spread of a thermal "Maxwellian" distribution at a given temperature, and a fast nucleus hitting one which is essentially stationary are all very different cases. Much of the published data is for "thermonuclear" machines such as tokamaks, and is not quite the same as for monoenergetic ions in an IEC machine. You may have to go back to the fundamental data to get a useful crossection.

The basic steps involved in calculating an approximate reaction rate are:

1) Determine the energy (charge on the ion times grid voltage to give electron volts) and corresponding fusion crossection (look up or calculate from known data). The crossection is usually denoted with the Greek letter lower-case sigma. Two crossections are used for IEC machines, the head-on equal-energy crossection and a lower crossection assuming that most collisions are at angles resulting from spherical convergence.

2) Determine the velocity of the striking nucleus. The velocity will be non-relativistic, and can be determined by the classical formula:

KE = 1/2 m V^2 (Kinetic Energy = one half particle mass times velocity squared)
or doing a little algegra --
V = sqrt(2 KE/m)

Be sure you pick a consistent system of units. In the SI system you must convert electron volts to joules (KE), the mass (m) of the nucleus to kilograms, and then the velocity (V) will work out in meters/second.

3) Calculate sigma V (the product of crossection and velocity).

4) Here is the messy part. Calculate the density of striking nuclei and the density of target nuclei. In the case of the D-D IEC machine described in the _Analog_ article these values are the same.

4A) The simplified approach to doing this is to assume all (or some large fraction of) the current to the inner grid is due to ion flow, each with a charge of +1 (there are 6.24e18 charges per ampere).

4B) One then multiplies the current times an "ion recirculation factor", starting with the geometric transparency of the inner grid (how much of the spherical surface is blocked by grid

wires). If 90% of the sphere is open space, and only 10% is blocked by wire, this should mean that an ion will hit the grid on only one pass in ten, so the first guess at the "ion recirculation factor" would be 10 (as we shall see in a minute, it can actually be much higher than this). Current times recirculation factor gives an estimate of the number of ions passing the grid per second.

4C) From the velocity of the ions and the diameter of the grid you can calculate how long each ion is inside the grid.

4D) From how long each ion is in the grid and how many ions per second pass through the grid you can calculate the overall density inside the grid.

4E) It is best to break this volume up into two or more concentric spheres or shells, with the central region a sphere the size of the visible bright spot in the very center. Density will be progressively higher as you approach the center. Fusion rate is strongly dependent on density.

5) For each shell, calculate the fusion rate. In the central region you use the lower angle-averaged crossection because the ions are hitting from all angles. In the shells surrounding it you use the higher head-on crossection, because the ions are traveling almost perfectly radially and only hit head-on. Fusion rate is essentially the product of the density of striking nucleus (ns), the density of target nucleus (nt), and the sigma V value already calculated. Since the target and striking densities are the same in this case you can just use ion density n so:

Fusion rate per unit volume = n n sigma V.

From there it is just a matter of geometry to calculate the volume of each region calculated, work up the fusion rate in that volume, and add up the rates.

This is an APPROXIMATION. More exact solutions require calculus to avoid the use of discrete shells and to account for the velocity and energy slightly falling off inside the inner grid (due to the mutual repulsion of ions concentrating there). Various loss mechanisms due to other forms of collision should also be taken into account, as well as various non-idealities. These are discussed in some of the referenced papers. However, down in the root of all of these fusion calculations you will find the factors "n-squared sigma V". It is important to recognize that the fusion rate goes up very strongly with increasing n (density) and somewhat strongly with velocity V (which is a function of energy, which also raises sigma).

If you look at specific cases of the calculation above, you will realize that a good, sharp focus of the central region of ion convergence will greatly increase the reaction rate there. In a well-focused machine this region produces most of the fusion, in spite of the lower reaction crossection, because the density is so very high there. In poorly-focused cases the region of head-on collisions outside the central focus region becomes more important: the density is lower but the higher crossection and greater volume compensate somewhat.

One interesting note: George Miley's group at the University of Illinois at Urbana-Champaign's Fusion Studies Institute have identified a phenomenon they call "star mode" (it was seen by Dr.

Hirsch as well and other workers as well, so is not new, but some of the earlier workers apparently did not fully appreciate the significance of it). If you get the machine described working right, you will see this mode, which essentially amounts to channelization of the ions into distinct rays converging on the center. The rays go through the grid openings, staying clear of the grid wires. In star mode, the effective transparency of the inner grid increases substantially over the geometrical transparency, possibly increasing transparency from a typical 90% to in excess of 99%, which increases ion recirculation up to 100 or even higher. Star mode also seems to sharpen the focus of the central convergence region. One key to star mode is achieving good alignment of the inner and outer grids.

Another interesting note: the pressure measured in the vacuum chamber by most common methods appears to be nearly useless for calculating density. If you assume the neutral gas is at room-temperature you might calculate a "mean free path" for collision between ions and neutral background gas and conclude the ions cannot travel far enough to achieve decent recirculation. However, performance of these machines suggests otherwise. Do remember that any background neutrals in such a machine will be slapped around rather rudely by the ions, which will typically have a kinetic temperature of 11604 K per electron volt, or 116 million K for a measily 10 kV drive voltage. Thus, the background neutrals should be expected to be rapidly heated to very high temperatures, which should greatly lower their density at any given pressure. Also, commonly used thermocouple gages assume the gas COOLS the gage, so if the gas is actually hotter'n the blazes of Hell, the gage will lie to you.

In essence, ion density responsible for the reaction will be a function of electrical current to the inner grid, recirculation efficiency, voltage, and sharpness of focus. The ions are largely trapped, thus do not interact with a pressure gage. No attempt should be made to try to determine ion density from chamber pressure as measured by a gage stuck out on the wall of the chamber. The gage pressure IS important, however, for achieving the neutral density needed to start up glow discharge mode, the easiest way of running these machines.

THE D-D REACTIONS AND NEUTRON DETECTION

Deuterium-deuterium fusion has two possible reaction pathways. Half of the time the products will be a tritium nucleus (one proton with two neutrons) and a free high-energy proton. The proton will not penetrate the vacuum chamber walls. The other half of the time the products will be helium 3 (two protons and one neutron) plus a free high-energy neutron, i.e. a “fast” neutron. Only very rarely does the reaction actually produce helium 4. Thus, the neutron production rate is half of the fusion rate. The D-D neutron comes off with an energy of ____ MeV, a characteristic which pretty conclusively identifies its fusion origin.

You will not be making enough tritium and helium 3 to significantly boost your reaction rate. However, the D-T reaction is the easiest fusion reaction and makes a very fast neutron (___ MeV). The D-He3 reaction usually takes a little more energy than the D-D reaction (probably will not be a significant reaction at the 10 keV range), and makes no neutrons.

Neutron counters with a construction similar to common Geiger counters are commercially

available. Two types are common, ___________ and ___________. Both are mostly used for detecting "slow" or "thermalized" neutrons around fission reactors. Their sensitivity to fast neutrons may be significantly off of their normal calibration, and usually they are used with "moderators" to convert the fast neutrons to the slow variety. A moderator uses either carbon or hydrogen or both to slow neutrons to ambient kinetic energy, or temperature, which is around 0.03 eV. Water, parafin wax, and polyethylene are common moderators. This type of counter may be sensitive to other forms of radiation, or even electrical discharges. One problem -- thermalizing the neutron obscures its fusion origin.

It is also possible to make certain elements radioactive using neutrons, then detect the resulting radioactivity. A favorite is indium, which has a very aggressive neutron capture crossection for partially thermalized neutrons, and the product decays fairly quickly. Be aware, however, that the machine described herein will make precious few neutrons, and detecting the resulting activation will be a serious challenge. Irradiating film may be the best and cheapest bet, but is time-consuming.

One of the slicker solutions is offered by scintillation plastics, which will emit a faint flash of light when struck by a fast neutron. This flash results from "proton recoil", part of the thermalization process. Most available scintillation plastics (which may be available quite cheaply from surplus dealers) detect a broad range of radiation types including fast neutrons, and some may even detect slow neutrons. However, Bicron makes one called BC720 which is virtually specific for fast neutrons. It may occasionally detect a strong gamma ray or two. You can buy this material, however it may be educational to look up the effect in the scientific literature, then make your own for a lot less money. The big advantage to buying it is that the manufacturer can tell you the sensitivity. Typically, a small block of BC720 will detect about 1% of neutrons coming from D-D fusion which actually pass through it, making it a reasonably sensitive detection method. To see the flashes of light, you need a blue-sensitive photomultiplier tube (PMT), preferably a bi-alkali type. I have not tried other methods, but POSSIBLY a CCD device, possibly even a very sensitive CCD TV camera, might detect the flash. There are CCD cameras for amateur astronomy with exceptional sensitivity. The human eye is also very sensitive to flashes of blue light when fully dark-adapted (supposedly you can see flashes of as few as 10 photons). This last method would mean sticking your head as close to a neutron source as possible, not the best of ideas for long-term use.

Whatever method you use, be ready for some careful thinking and developing a full understanding of the method. The count you measure is NOT the neutron production rate! The counter only sees a certain fraction of the neutrons which pass through its detector. Many counters are calibrated in "dosimetry" units such as rads (radiation absorbed dose) or rems (radiation equivalent mammalian), useful for keeping nuclear workers healthy but requiring some conversion if what you really want is neutrons produced. Getting a neutron counting system calibrated is no trivial task -- only a couple of outfits in the U.S. do it. This is an area where a good health physics advisor is especially valuable.

TERMS AND TOPICS IT WOULD BE HELPFUL TO UNDERSTAND

Spherical Geometry (Surface area and volume of spheres and shells)
Inverse Square Law
Fission versus Fusion
Conversion of Mass to Energy (E=mc^2)
Hydrogen, Deuterium, Tritium, and their reactions
Plasma
Ions and Ionization
Mean Free Path
Molecular Flow Regime
Viscous Flow Regime
Vacuum Pump Types and Capacities
Vacuum Valves and Other Hardware
Outgassing
Virtual Leaks
Ideal Gas Law (density vs pressure vs temperature)
Force on a Charged Particle Produced by an Electric Field
Debye Length
Coulomb Repulsion
Poisson's Equation, especially the Spherical Case (requires advanced calculus)
Operation of primitive linear particle accelerators
Related equpment:

- Electron and ion guns
- Cathode Ray Tubes
- Mass Spectrometers (especially Time-Of-Flight instruments)
- Auger Electron Spectrometers

Crossections for collision types:

- Ion-ion (simple collision)
- Ion-electron (recombination to form neutral)
- Ion-neutral Charge Exchange
- Ion-Ion (fusion)
- Neutron-nucleus (capture)
- Neutron-nucleus (slowing and thermalization)

Glow Discharge
Paschen Curve
Thermionic Emission
Electronic Vacuum Tube Theory
Space-Charge and Space-Charge Limitation
Vacuum Gage Types:

- Burdon Tube
- Thermocouple
- Capacitance
- Ionization
- Cold Cathode

If you can gain a fundamental understanding most or all of these topics at the high school science

level, and then employ them to make a working fusion reactor, you ought to be a good candidate for national honors in a science fair competition. Much of this is actually pretty simple, but taken as a whole it is a considerable body of knowledge.

USEFUL SOURCES FOR LAB TECHNIQUES AND EQUIPMENT

PATENTS

CORRECTION of RWB patent in Ref 8.

SOME RELEVANT PAPERS

WEBSITES

TRADEMARKS

The use of trademarks herein is intended to provide examples of products believed to be of good quality, rather than a specific requirement or recommendation.
Lexan is a trademark of GE.
Plexiglas is a trademark of Rohm and Haas
Teflon is a trademark of Dupont.
Variac
20-mule team (U.S. Borax)
Moto-Tool
Swage-Lok
Snoop

SOURCES OF SUPPLY

Amateur Radio Hamfests: ARRL Website. These magnificent junksales can turn up the most amazing hardware! Richard Hull has occasionally found good vacuum pumps and other vacuum hardware at them at bargain prices. High voltage components of various types are usually available, usually at a tiny fraction of the new price. You might even find nuclear science hardware such as Geiger counters. Or, you might meet Richard himself!

- Videotapes on Fusors, exotic metals
  - Richard Hull
- Surplus Nuclear Science Equipment
  - O. E. Tech
- Surplus Vacuum Equipment
  - T. S. Vacuum
  - Duniway Stockroom
- Neon Sign Transoformers
  - Neon Sign Suppliers
  - ` Electricians doing commercial remodeling
- Alumina tube, other industrial supplies
  - McMaster-Carr
- Diamond Cutoff Wheels (and lotsa neat junk)
  - American Science and Surplus
- High Voltage Resistors
  - MECI
- High Voltage Rectifiers
  - MCM Electronics (microwave oven diodes)
- Adjustable Autotransformers
  - MCM Electronics
- Photomultiplier Tubes, other electronics.
  - MPJA
- Vacuum Apparatus and Supplies, New
  - Kurt J. Lesker (good catalog, too)
  - MDC
  - ISI
- Porcelean Insulators and other electronic supplies
  - Newark Electronics
- Books
  - Lindsay Press